Lessons Learned and Experiences Gained in Developing the Waterflooding Concept of a Fractured Basement-Granite Reservoir: A 20-Year Case Study

C.T.Q. Dang, SPE, and **Z. Chen,** University of Calgary; **N.T.B. Nguyen,** SPE, and **W. Bae,** SPE, Sejong University; and **T.H. Phung,** Vietsovpetro Joint Venture

Summary

Naturally fractured reservoirs (NFRs) represent more than 20% of the world's oil and gas reserves. However, their characterization is complex and presents unique challenges in comparison with conventional reservoirs. It is immensely difficult to achieve the best results in the secondary-recovery process for NFRs.

This paper presents a successful development of waterflooding to overcome the complex geological characterization of the White Tiger field, the largest fractured basement reservoir to date on the continental shelf of Vietnam. This reservoir has a complicated geological structure, with high heterogeneity, high temperature, and high closure stress. The total oil initially in place (OIIP) of this field reached nearly 4 billion bbl from 2000 m of oil-bearing thickness, and the field has been produced by more than 100 wells, 10 of which have flowed at the rate of approximately 1,000 B/D.

The geological study and fractured model have been carefully investigated in both micro- and macroscale to improve waterflooding performance. The authors have analyzed the advantages and disadvantages of injection systems in this basement reservoir during 20 years of production history, and an artificial water buffer solution has been proposed to improve the waterflooding process. The authors have described the establishment and association of local artificial water buffer in the basement reservoir. An effective method to optimize the injected-water volume has also been discussed. Promising results from the White Tiger field have shown that the average reservoir pressure and total oil recovery have increased significantly in comparison with previous injection schemes.

This paper presents useful guidelines to solve some typical problems of waterflooding in fractured basement reservoirs:

• What can be applied in waterflooding for a fractured basement reservoir?

• What is the optimal injection rate and injected volume for the fractured basement reservoir?

• How do we evaluate the probability of high water cut in production wells during the waterflooding process?

• How do we predict the rise of an artificial water/oil contact (AWOC)?

Introduction

NFRs are oil and gas reservoirs whose rock matrices contain pores, pore throats, and natural fractures. NFRs represent more than 20% of the world's oil and gas reserves. They play an important role in oil exploration and make a large contribution to oil and gas production worldwide. The research increase in NFRs has become more apparent in the last decade because more fractured reservoirs are being developed. However, characterization of fractured reservoirs is complex and presents unique challenges in comparison with conventional reservoirs. There are several uncertainties in NFR characterization in exploration and field-development strategies, especially in the early stages when few or even no data are available. Thus, it has become necessary to collect the experiences from previous successful research to reduce the risks.

Fractured basement reservoirs are usually deep, and not much research has been conducted that explains them. Proper understanding of fractured-basement-reservoir characterization helps engineers use suitable methods in drilling, well completion, production, and improved or enhanced-oil recovery (EOR). In the past, fractured basement reservoirs were discovered by accident [e.g., the La Paz field in Venezuela (the NFR discovered before 1950) and the White Tiger field (producing since 1986, and the first oil field in Vietnam)]. **Table 1** shows a summary of basement-rock reservoirs in the world. Most of these reservoirs had low production rates (e.g., 19−149 m^3/d at the Orth field, 8.7−69 m^3/d at Beaver in the US, and 33.4−120.2 m^3/d at the Xinlongtai field in China). However, the White Tiger field in Vietnam **(Fig. 1),** which is the biggest fractured basement reservoir to date on the continental shelf of Vietnam, has flowed at more than 28 620 m^3/d (Nguyen and Le 2004). This reservoir has a complicated geological structure, high temperature (greater than 140°C), and high closure stress (greater than 414 atm); the collector model is quite different from that of conventional oil reservoirs in sedimentary rocks. The total OIIP of this field reached nearly 636 million m^3, with 2000 m of oil-bearing thickness, and the field has been produced by more than 100 wells. Thus, White Tiger has become one of the rarest oil fields worldwide. After the White Tiger oil field was discovered, numerous new basement reservoirs in the Cuu Long basin have successfully found potential production [e.g., the Rong field (reserves of approximately 6.36 million m^3), the Ruby field (initial production is approximately 3180 m^3/d), the Rang Dong field (initial production is approximately 9540 m^3/d), the Su Tu Den field (initial production is approximately 9540 m^3/d), and the Ca Ngu Vang field (preliminary reserves of approximately 14.31 million m^3)]. The discovery of the oil reservoir in the White Tiger fractured basement has changed the concept of oil and gas prospecting, exploration, and development in Vietnam and the region, providing a considerable contribution to the world's oil and gas science.

Statement of Problem

The use of secondary-recovery processes has become more imperative. Waterflooding is one of the most widely used secondary-recovery means of production after primary energy has been exhausted. It was usually applied in conventional reservoirs, but had little success in NFRs, although numerous attempts were made. Waterflooding in NFRs can be uneconomic because of extremely complex geological characterization and poor oil-recovery performance. Numerous failures have been from lack of knowledge of reservoir geological characteristics and proper waterflooding techniques. NFRs are characterized by two distinct media: a relatively tight matrix with insignificant permeability and a fracture system with significant permeability. This distinction in permeability may result in rapid water breakthrough during a waterflooding process, depending on the wettability of the matrix.

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TABLE 1—BASEMENT-ROCK RESERVOIRS OF THE WORLD*

Reservoir	Region	Lithology	Reservoir Fluid	Discovered Time	Highest Production	Depth
Aerxia field, Yumen	China	Metamorphic rock	Oil and gas	1959	700–1,050 B/D	2600–3200 m
Clair field	UK	Granite	Oil	1977	2,100–3,000 B/D	1000–2000 m
Dragon field	Viet Nam	Granite		1990s	8,000 B/D	
El Segundo field	California, US	Schist conglomerate	Oil	1937	4,563 B/D	2210 m
Furbero oil field	Mexico	Gabbro	Oil	–	1,000 B/D	–
Java-Jatibarang field	Indonesia	Volcanic breccia	Oil and gas	1969	250–3,000 B/D	2000–2300 m
Kraft-Prusa field	US	Fractured quartzite	Oil	1945	65–108 B/D	969–1017 m
La paz field	Venezuela	Limestone, granite	Oil	1922	5,000 B/D	2709 m
Mara field	Venezuela	Granite and metamorphic rock	Oil	1956	2,700–17,000 B/D	363 m
Nafoora-Augila field	Libya	Granite	Oil	–	1,200–7,627 B/D	2600 m
Nagaoka and Niigata field	Japan	Green tuff and volcanic formations	Oil and gas	–	5,400 BOPD and 14 bcf gas	–
Orth field	US	Fractured quartzite	Oil	1952	120–939 B/D	–
Playa del Rey field	Venice, US	Schist	Oil	1929	400 B/D	–
PY-1 field	India	Weathered granite	Gas and condensate	1980	13 mmcf/day	5,000–5,500 ft
Shaim field	Russia	Granite and gneiss	Oil	1959	25–28 B/D	-
Silica field	US	Fractured quartzite	Oil	–	100 B/D	997–1001 m
Sumatra-Beruk Northeast	Indonesia	Metaquartzites, weathered granite	Oil and gas	1976	1,680 B/D	1,634 ft
White Tiger field	Vietnam	Granite	Oil and gas	1986	180,000 B/D	5000 m
Wilmington field	California, US	Schist	Oil	1945	1,200–2,000 B/D	1764
Xinglongtai field	China	Metamorphosed granite	Oil and gas	1976	210–756 B/D	8000 m
Zeit Bay field	Egypt	Fractured Granite	Oil	1981	700–10,000 B/D	–

* from http://www.geosciences.co.uk

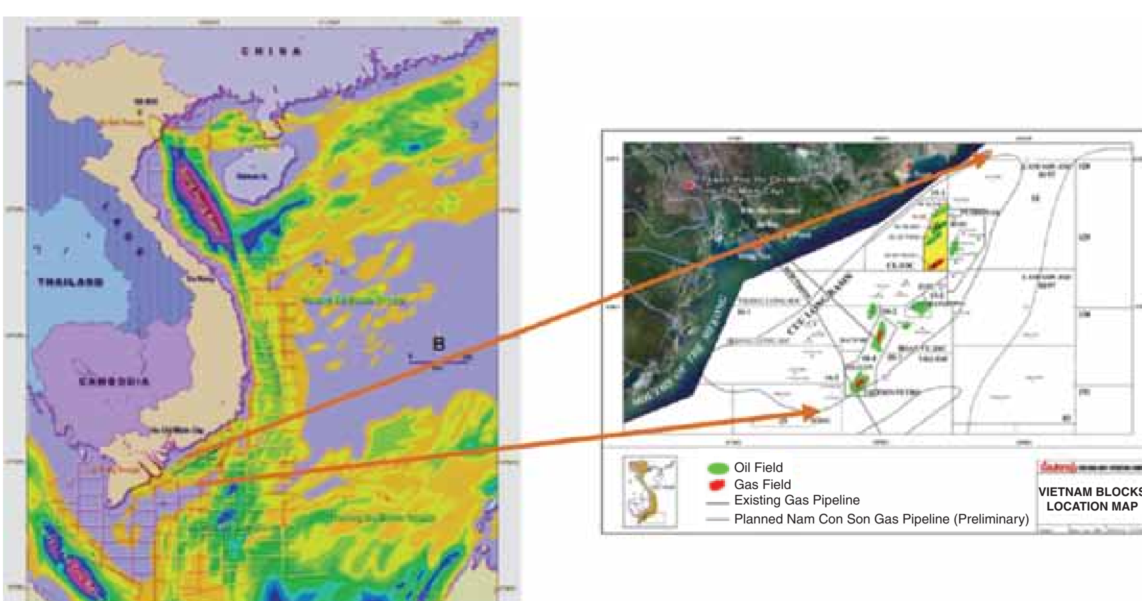


Fig. 1—Location of the basin in the Vietnam continental shelf and the White Tiger location in the Cuu Long basin.

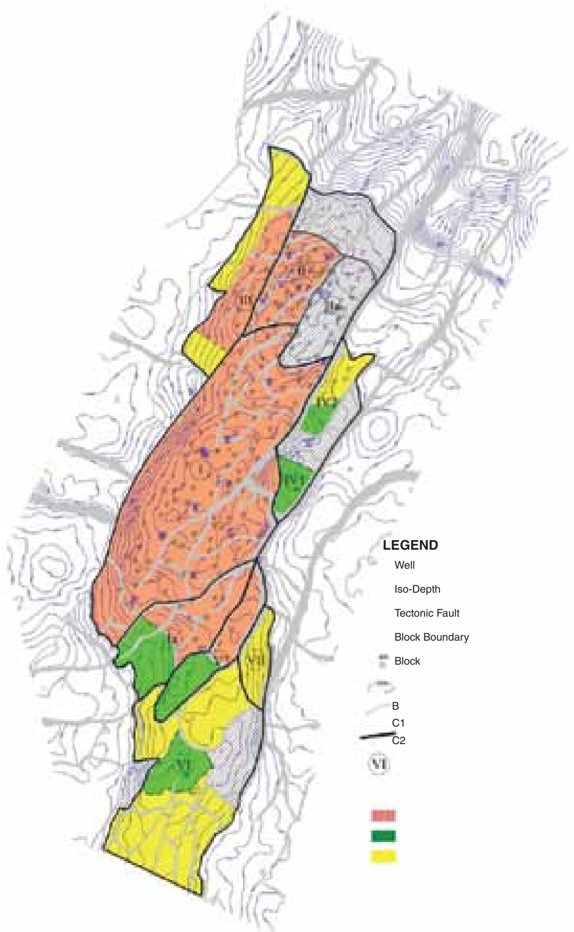


Fig. 2—Structural map of fractured basement reservoir.

This paper first introduces the unique geological characteristics in the fractured basement reservoir of the White Tiger oil field. On the basis of a thorough understanding of geological properties, the development of the waterflooding concept and lessons learned from a long history of operation in this fractured basement-granite reservoir are discussed in this paper. With rich experiences in exploration and production of hydrocarbon in fractured basement-granite rocks for more than the past 20 years, it is a valuable case study for both current and future development planning of basement reservoirs elsewhere in the world.

Geological Overview of Naturally Fractured Basement Reservoir in White Tiger Field

The study of the fractured reservoir begins with a detailed analysis of the geometry, origin, morphology, density, width, trace length of fractures, and the development of porosity and storage-capacity systems of the reservoir rocks. These parameters control the borehole diameter (relative to the spacing of fractures) and the trajectory of the boreholes (relative to the orientation of fractures). Three main formations in the basement of the Cuu Long basin, which contribute to the oil-bearing reservoir, are the complexes of Hon Khoai, Dinh Quan, and Ankroet. These rocks were formed approximately 90 million to 240 million years ago (Hoang 2008). Regarding the geological characteristics and hydraulic communication, the fractured basement was divided into two main structures, including centre (Blocks 4, 5, 6, and 7) and northern structures (Blocks 2, 3, and 4), as shown in **Figs. 2 and 3.**

Most basement rocks in the Cuu Long basin are hard and brittle. Fractures, faults, and vugs contribute to the porosity. There are no pores in the matrix. In the continental shelf of Vietnam, basement reservoirs are located under unconformities and on the highs of uplifted blocks that are weathered and eroded. These basement reservoirs are covered by younger sediments [e.g., source rocks and caprocks **(Fig. 4)**].

The distribution of different rock types in fractured basement reservoirs of the White Tiger field is shown in **Fig. 5.** The lithology is an important controlling factor for reservoir quality. The reservoir quality of basement rock in the Cuu Long basin depends on the development of secondary porosity. Two main types of porosity are tectonic porosity (fractures and faults) and dissoluble porosity (caverns; **Fig. 6**). The fractured zones are mainly concentrated at the top of the basement. However, the basement reservoir is thick. For example, the White Tiger basement reservoir has oil-bearing thickness of nearly 2000 m in length and width of 30 km and 6 to 8 km; it is located in the central uplift zone of the Cuu Long basin. The depth of the oil-bearing zone varies from 3700 to 4450 m at the boundary of the reservoir and from 4000 to 4200 m at shallower intervals.

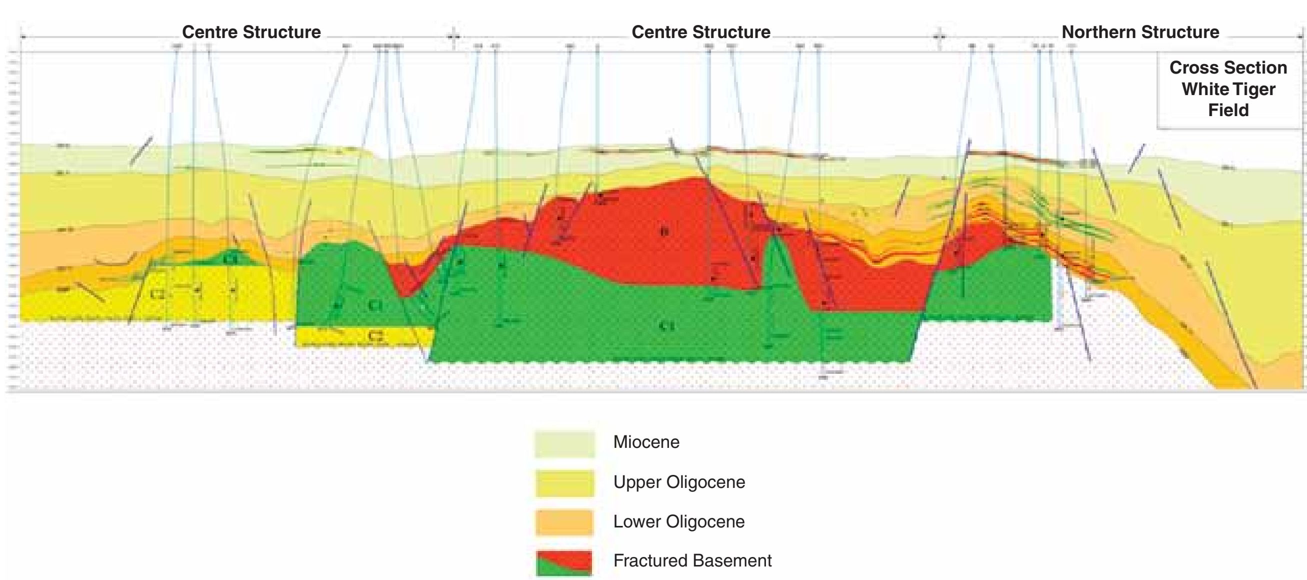


Fig. 3—Cross section of White Tiger field.

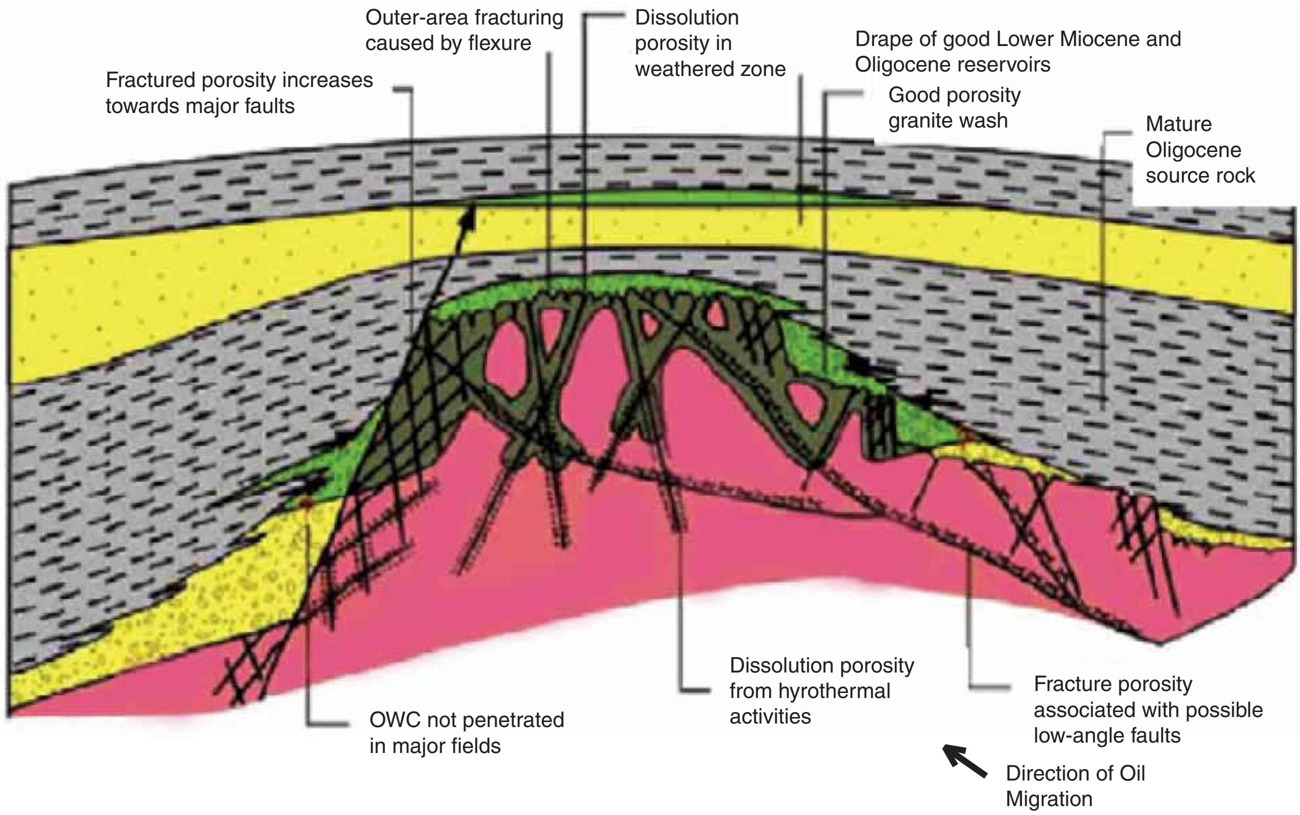


Fig. 4—Petroleum play concept in the Cuu Long basin and fracture porosity in basement reservoir (Nguyen and Le 2004).

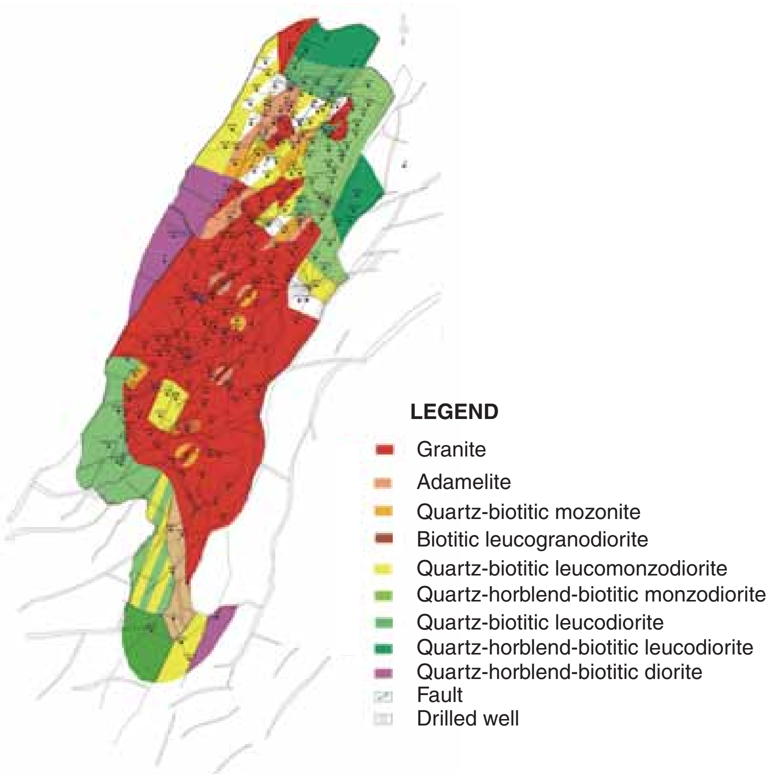


Fig. 5—Lithology distribution in fractured basement reservoir.

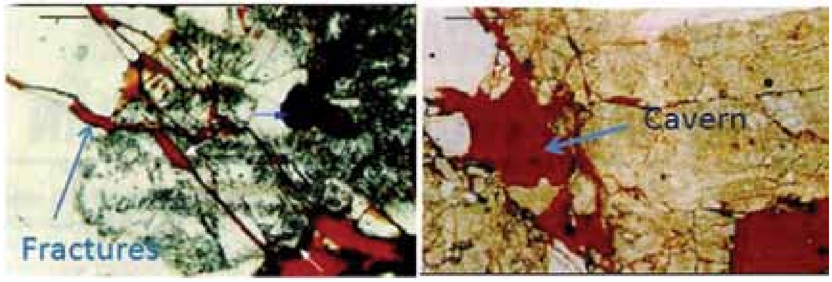


Fig. 6—Fractures and caverns in basement-rock reservoir of Cuu Long basin (Trinh 2001).

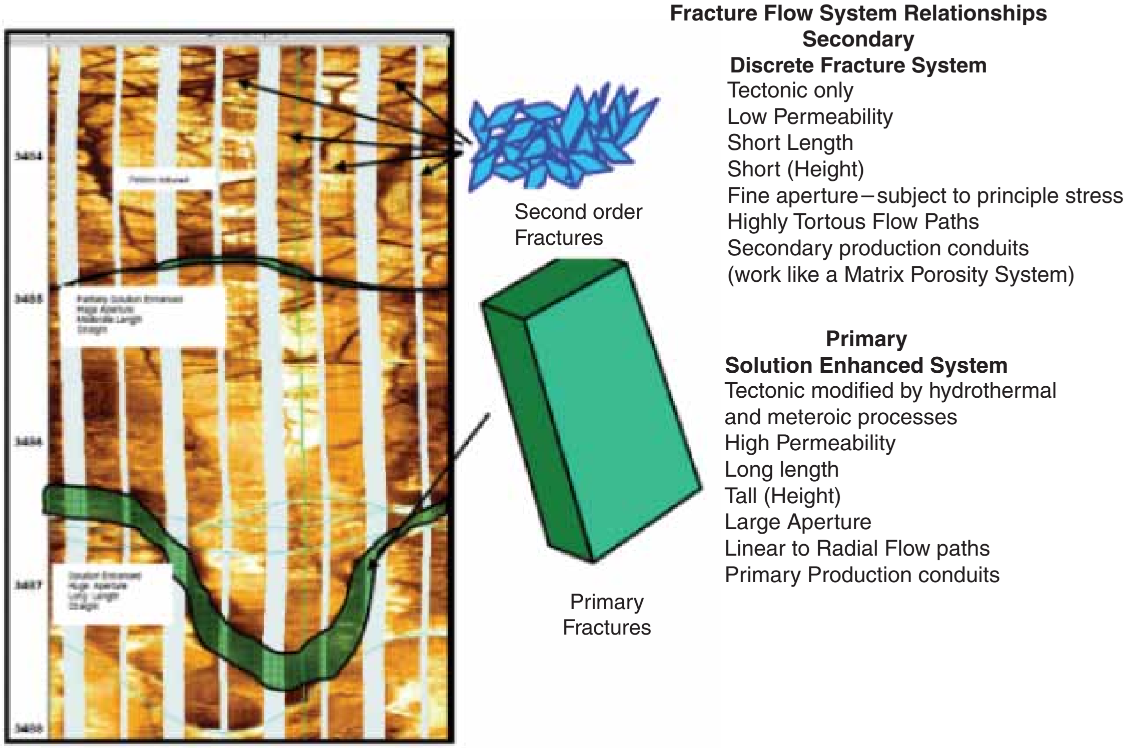


Fig. 7—Fracture-classification system used for basement reservoir in Cuu Long basin (Li et al. 2004).

Fracture/Fault Characteristics. The tectonic activity is the main cause of the formation of fractures and faults. These fractures and faults were developed during three main stages: the Jurassic/Cretaceous orogenetic compression, the Late Cretaceous extension and intrusive activities; the Oligocene extension and Late Eocene/Oligocene rift; and the Late Oligocene/Early Miocene compression (Nguyen et al. 2001). In the White Tiger field, fractures have played an important role in storing and transferring oil from the reservoir to production wells. Therefore, fracture properties are important parameters for studying reservoir characteristics. In the investigated and measured results of tectonic scratches on the onshore outcrops and seismic data, the dip angles of the faults and fractures are mostly greater than 40° and their azimuths are mentioned in the studies of Tran et al. (2001) and Nguyen et al. (2001). The north/east, east/west, and north/west systems are developed with the highest density. This system is important for contributing porosity to the basement reservoir (Li et al. 2004; Tran et al. 2006).

In the Nelson classification, the fractures of the Cuu Long basin basement reservoirs can be classified into two major types. The first type is bounding solution-enhanced fractures, which contribute the most pore space and permeability. The second type is discrete fractures, which have small apertures and low permeability (**Fig. 7;** Li et al. 2004).

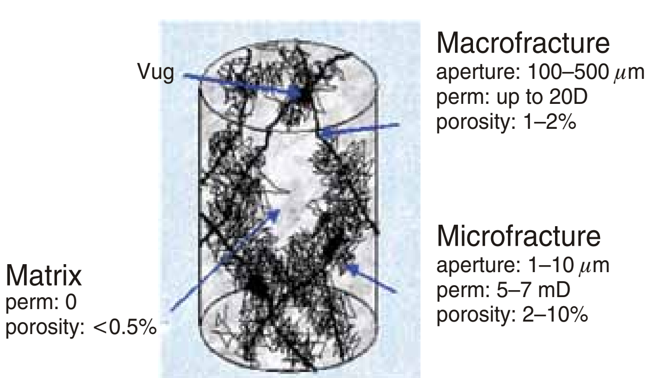


Fig. 8—Pore-space structure in White Tiger basement reservoir (Hoang et al. 2008).

Reservoir Properties. The basement-granite reservoir of the White Tiger oil field can form a good oil-bearing reservoir because of its high density of fractures in the uplifted block. The oil was generated in the younger sedimentary rock and then migrated and ac-

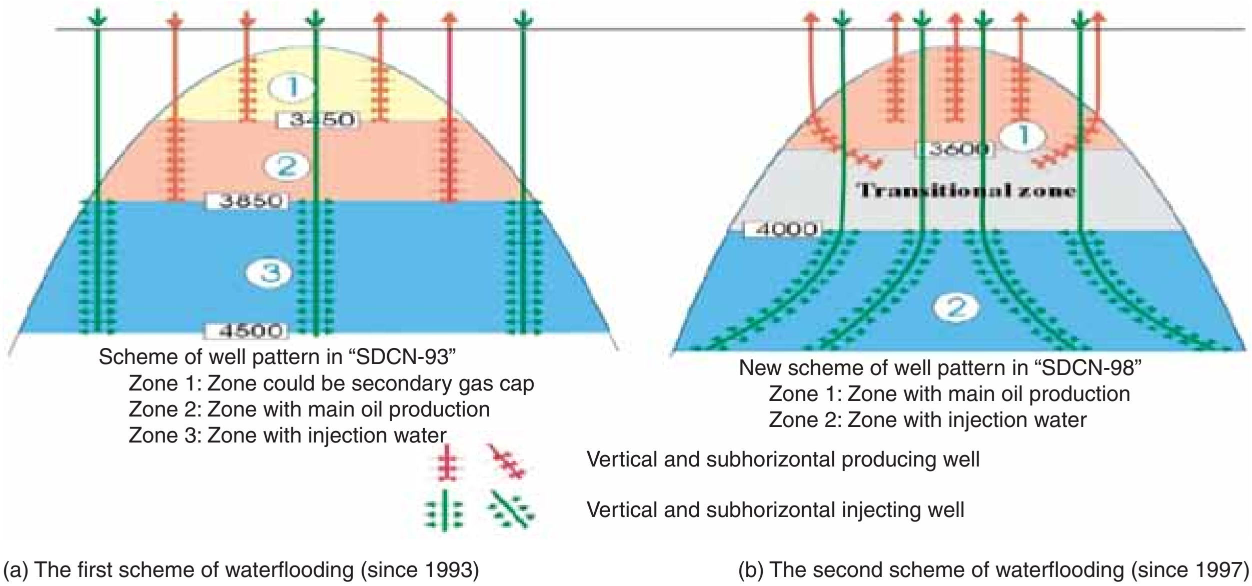


Fig. 9—The waterflooding scenarios for the fractured basement reservoir in the White Tiger field.

cumulated in the basement rock during the post-Oligocene tectonic movements. The migration mechanisms of oil are from permeable units to active faults at the basement and cover interface. As confirmed by laboratory and field studies, the igneous-rock reservoirs contain a small amount of matrix porosity, which was formed by cooling magma (primary porosity), and a large amount of secondary porosity formed by tectonic activities (fractures, joints, and faults) and dissolution (vugs). Moreover, Nguyen et al. (2008) identified that the pore structure of the granite basement rock in the Cuu Long basin was characterized by high heterogeneity and complexity. Those pores were the result of various processes (e.g., heat shrinkage and expansion of magmatic bodies, tectonic movements, hydrothermal impacts, and weathering). The porosity range from 2 to 5% represents a good reservoir quality. In a study by Phung et al. (2008), the porosity of the Dragon oil field varied in a range from 0.22 to 15.04%, averaging 2.87%, as measured from the core plugs and logging and a 1.48% thin section.

Fig. 8 reconstructs the porosity distribution in the Cuu Long basin basement reservoirs. Porosity is divided into four zones on the basis of the density of fractures: (a) Zone 1 is a fracture; (b) Zone 2 is highly altered rock; (c) Zone 3 is mildly altered rocks; and (d) Zone 4 is less-altered or nonaktered rocks. In the White Tiger field, the porosities were studied and showed that the two main types were macrofractures and microfractures (Fig. 8).

Development of Waterflooding Concept in the White Tiger Field

The fractured basement reservoir in the White Tiger field has been producing since 1988. This reservoir was produced under a natural primary drive mechanism from August 1988 to June 1993. Since then, waterflooding has been applied to maintain the reservoir pressure. It is a closed reservoir and without a bottom or edge aquifer. Experience with the waterflooding process in such reservoirs is limited across the world. A large amount of oil (17 million tons) was produced from this field before waterflooding, and it was not possible to keep the average reservoir pressure above the bubblepoint pressure (Vietsovpetro 1998). In order to achieve a successful waterflooding process, four main questions had to be addressed:

- Can waterflooding be applied in this fractured basement reservoir?
- What are the optimal injection rate and injected mass?
- How do we evaluate the probability of high water cut in production wells during the waterflooding process?
- How do we predict the rise of AWOC?

Before injection, the reservoir-characterization studies (including wettability, relative permeability, and hydraulic dynamic connection of wells) were thoroughly investigated at laboratory scale. **Fig. 9** shows the difference between the two main stages (1993–98 and 1998 to present) of the waterflooding process in the White Tiger field.

The Initial Waterflooding (1993–98). According to this plan, the fractured basement reservoir was divided into three zones:

- The first zone from 3050 to 3450 m is a potential gas-cap zone.
- The second zone from 3450 to 3850 m is the main production zone.
- The third zone from 3850 to 4500 m is the injection zone.

All of the injection wells that were drilled in the fractured basement reservoir are vertical wells. This pattern was based on the idea that when the amount of injected water is not enough to compensate for production, the average reservoir pressure drops below the bubblepoint pressure and a secondary gas cap will be formed in the reservoir. Water was injected into the bottom regions, while gas was injected into the top of this basement reservoir. The forces in the two opposite directions push oil into the main production zone. This is the main advantage of this scenario. However, production decreases as the reservoir pressure drops below the bubblepoint pressure and consequently the cumulative oil recovery will be decreased significantly.

The Second Stage of Waterflooding (1998 to Present). From 1998 to 2003, a new approach for waterflooding in fractured basement reservoirs was proposed and applied in the White Tiger field. The mechanism of the waterflooding process in this scenario is similar to piston displacement. This scheme includes two zones. The main production zone is from 3050 to 3600 m, while water was injected at below 4000 m in depth. There is a transition zone from 3600 to 4000 m. The ratio of production wells to injection wells is approximately 3:1. Most of the injection wells are located in the central structure of the reservoir. The well distribution in the fractured basement reservoir is shown in **Fig. 10.** The keys of this pilot are described as follows:

- Water was injected into the bottom of the reservoir.
- Horizontal wells and directional wells for the waterflooding process are applied, and the well density is 1000 × 1000 m and will be dense during the operation period.
- The trajectory of both injection and production wells is perpendicular to the developed direction of fracture systems. Then, the sweep efficiency was improved significantly.

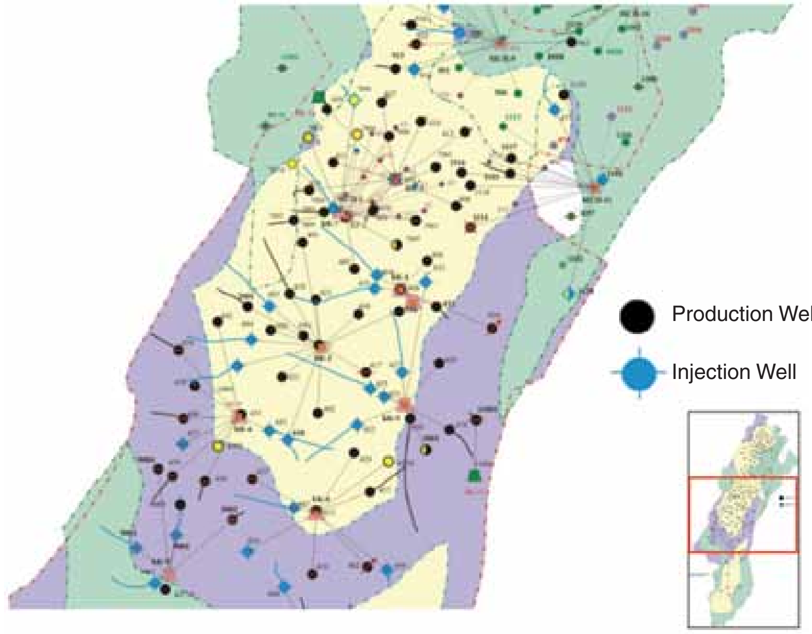


Fig. 10—Well distribution in fractured basement reservoir.

TABLE 2—RESULTS OF DYNAMIC AWOC IN FRACTURED BASEMENT RESERVOIR		
Group	Selected Production Well	AWOC (m)
I	78, 7449, 7476, 7462, 7419, 7457, 7415, 7429, 7423, 7438, 7431, 7439, 7440, 7436, 7479	3552
II	7442, 72001, 7420, 7428, 7421, 7432, 72, 7409, 7402, 7417, 7426, 7456, 75001, 7478	3482
III	7450, 7413, 77001, 7411, 7491, 7403, 7407, 71, 77006, 7430, 7401, 7410, 7412, 71116, 77003, 7404, 71111, 71118, 71117, 7556, 7432	3401

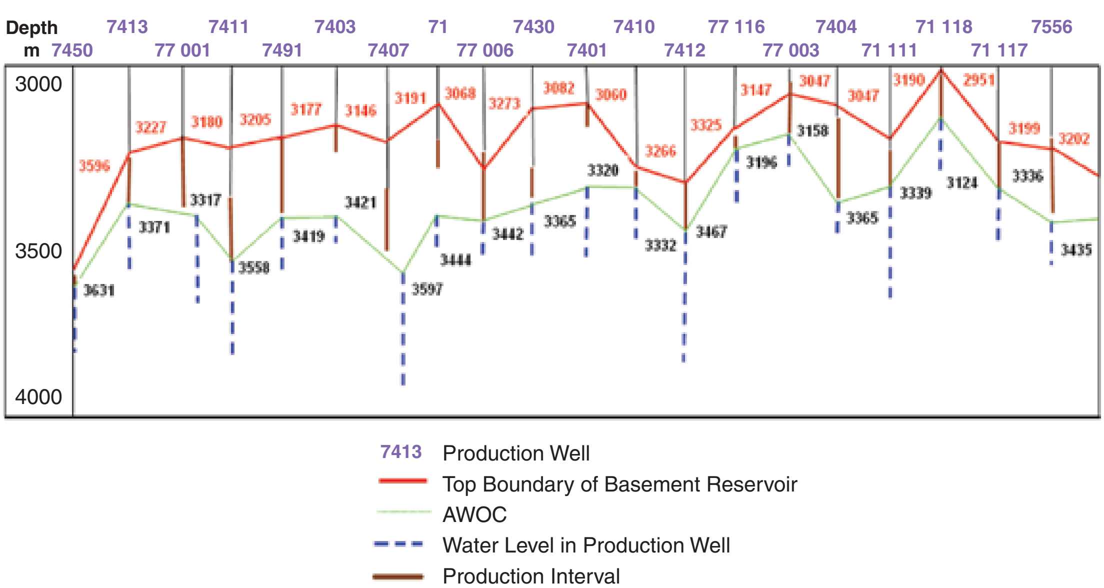


Fig. 11—The AWOC of production wells at 3382 m in depth.

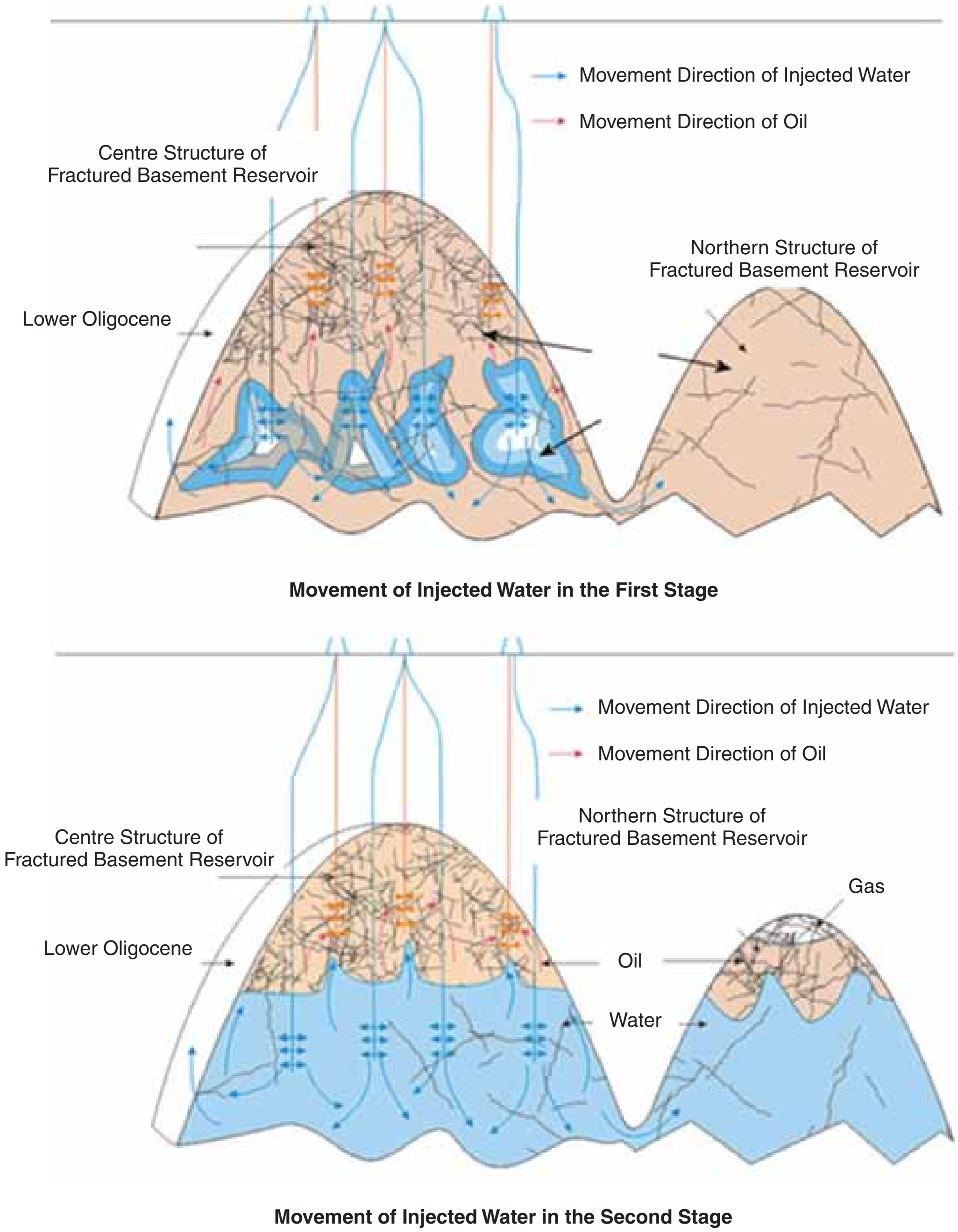


Fig. 12—The movement mechanism of injected water in a fractured basement reservoir.

- The injection wells must be located in the entire reservoir in order to have the highest areal and vertical sweep efficiency.
- As the water/oil contact rises, the production zone will be moved to the upper part of the basement reservoir.
- The injection wells can be replaced with production wells in the top of the reservoir.

In this scenario, the artificial water buffers were formed and effectively pushed the remaining oil into production wells. Moreover, the average reservoir pressure was also kept at a higher value than that in the first scenario. The application of horizontal and directional wells for the purpose of injection plays an important role in improving oil recovery in fractured basement reservoirs.

The Generation and Combination of Artificial Water Buffers. More than 174 million m^3 of water was injected into the fractured basement reservoir at 4000 m in depth from June 1993 to the end of 2005. The water initially was injected under a high injection pressure and gravity force; however, the permeability in deeper horizons ranges only from 5 to 30 md. Therefore, the injected water tends to stay near the injection-well regions and form artificial water buffers. The combination of artificial water buffers is quite slow. These artificial water buffers do not have any specific shape that depends on reservoir structure, reservoir shape, and permeability of injected zones. In December 1998, an investigation in 47 wells was conducted and indicated that the injected water existed in 14 wells. The water cut varied within a wide range from 1 to 66.7%. In addition, 33 wells, which were operated from 3020 to 4550 m in depth, did not have water in production, proving that an artificial water buffer had not formed.

Another study was conducted in 2000 in which most of the wells in the fractured basement reservoir were flooded below 3800 m in depth. It was found that the injected water no longer moved downward, whereas water was separated in the horizontal direction or moved upward following the vertical fractures. This mechanism

Injection Well/ Production Well	Movement Time (day)	Movement Speed (m/d)
7405→7411	1348	0.3
7464→7413	113	0.351
7464→7428	637	0.136
7435→7420	564	0.179
7435→7428	502	0.136
7455→7420	1158	0.179
7425→7417	1356	0.484
7905→7902	1222.5	0.051
7905→7904	1252.5	0.086
7421→7409	750	1.35
7804→7803	920	0.148
7804→7811	1244.5	0.066

TABLE 3—HYDRAULIC RELATIONSHIP BETWEEN INJECTION AND PRODUCTION WELLS

generated a large artificial water buffer and initially the formation of a water/oil contact in the central structure of this fractured basement reservoir. In the northern structure, the hydraulic connection between wells is limited because of high heterogeneity. Thus, the forming of an artificial water buffer was difficult and slow. The results of production logging tool tests showed that the AWOC moved upward approximately 37 m in 1 year. Three groups were selected for studying the dynamic AWOC. The results are shown in **Table 2.** In combination with the results in the northern structure, a detailed image of the AWOC was constructed **(Fig. 11).**

Fig. 12 shows the movement mechanism of the injected water in the fractured basement reservoir. There are two stages to explain the movement of the injected water in the basement reservoir. In the first stage, waterflooding moved oil upward through the main vertical fractures in this reservoir. Then, in the second stage, waterflooding was applied in the basement reservoir. The water was injected at below 3900 m in depth. Under the injection pressure and gravity force, the injected water was located in the bottom of the reservoir because of a low permeability value. This is marked as the local water buffers. After 2000, the average reservoir pressure in numerous wells is similar and the water cut is also stable. It was demonstrated that the different local water buffers combined to form a large artificial water buffer. This increases the hydraulic connection of different wells and pushes oil into production wells. However, the injected water quickly moved into production wells in worse cases because of vertical macrofractures. It happened in several production wells located near large fractures with high permeability. The water cut sharply increased from zero to 63% after only a few months, and the oil could not be produced by natural drive. Setting of a cement bridge should be first applied to isolate the water zones; otherwise, the production well will be destroyed by injected water.

Numerous methods were applied to investigate the hydraulic relationship of injection wells and movement of the injected water from injection wells to production wells. The relationship is complex and difficult because of the extreme complexity of fracture systems in the basement reservoir. The water was injected into the reservoir and separated into numerous different directions. Only a part of the injected water actually moved from injection to production wells. The results in **Table 3** indicate that 113 days is the minimum time of movement for the injected water moving from injection to production wells. And then, a tracer test was applied in the White Tiger field, and it required 1 to 140 days for the injected water to move from three injection wells (7911, 7914, and 7921) to production wells (760, 7412, 7901, 7902, 7904, and 7920). This means the movement of the injected water is fast after forming of

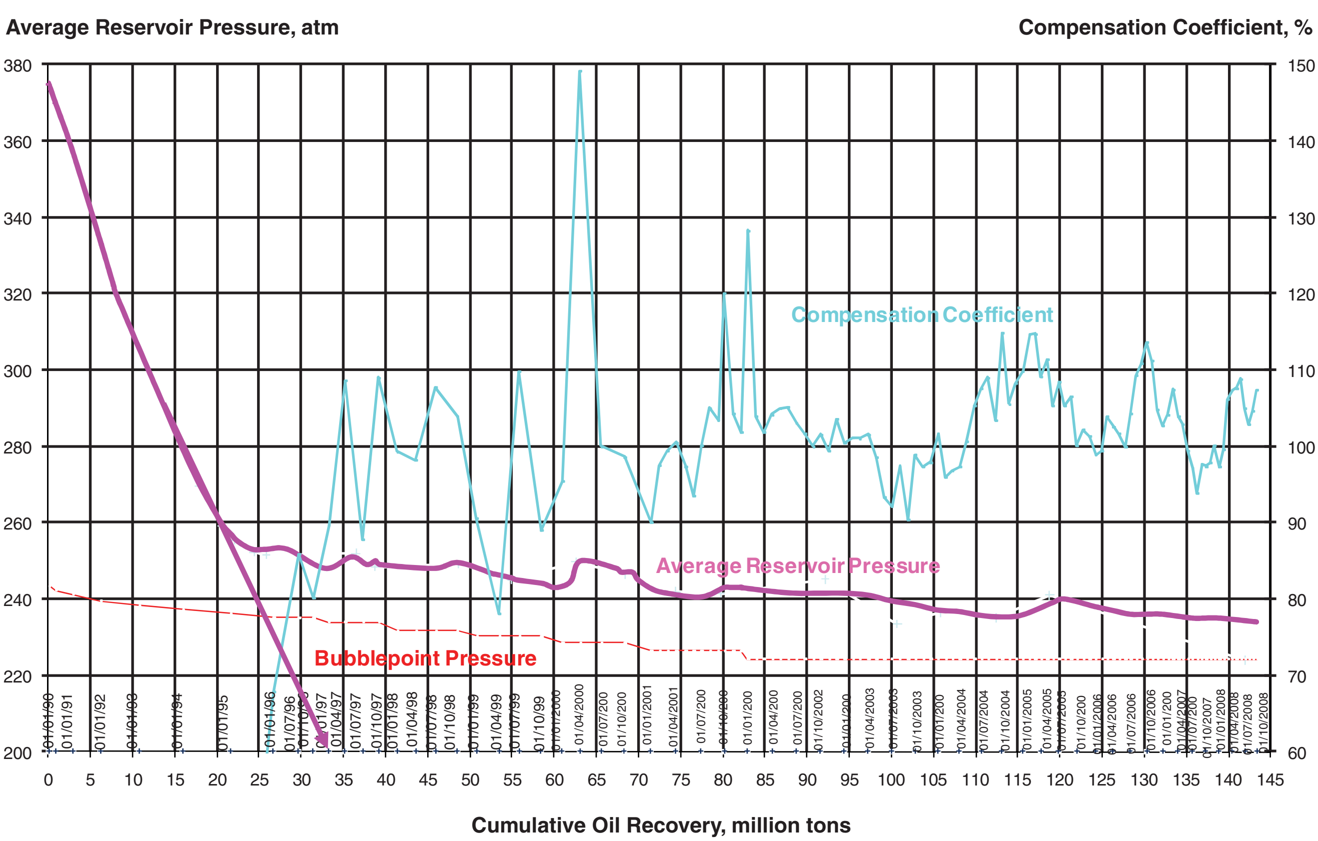


Fig. 13—The relationship between average reservoir pressure and the compensation coefficient.

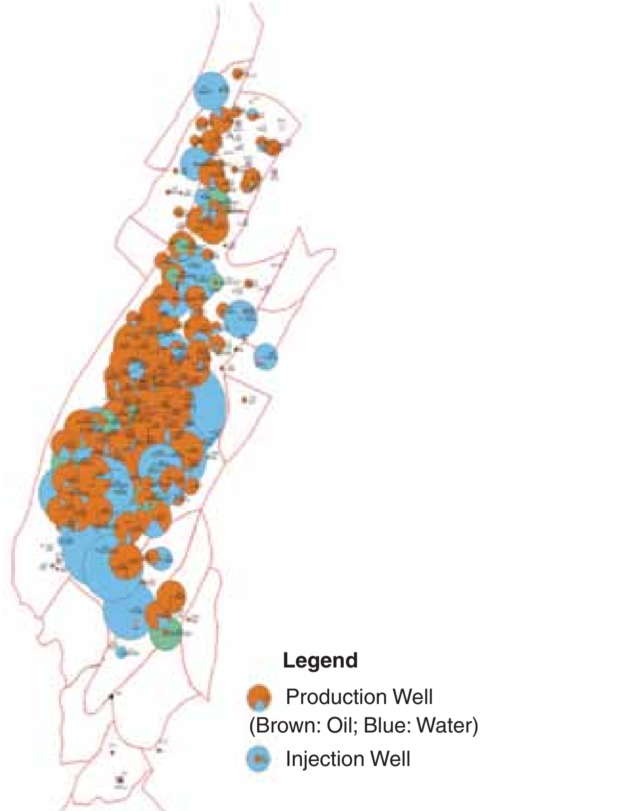


Fig. 14—The injection and production map in a fractured basement reservoir (1 January 2010).

hydraulic channels. This is an important factor that the reservoir engineer must consider when operating waterflooding in fractured basement reservoirs. As the water cut sharply increases, the cumulative oil recovery will drop significantly. The water cut value of some production wells in the fractured basement reservoir of the White Tiger field increased from zero to 50% after only 2 months.

The Effect of Injected-Water Volume on Reservoir Pressure. The reservoir pressure strongly depends on the volume of injected water, as shown in **Fig. 13.** The reservoir pressure rapidly decreased from 41 MPa (initial reservoir pressure) to 25.5 MPa after 7 years of production because the injected water is not enough to compensate for the amount of produced fluid. The average declining rate of pressure was approximately 38.8 atm/yr and the reservoir pressure dropped below bubblepoint reservoir pressure on 1 January 1996. The maximum oil recovery is only 33 million tons of oil (approximately 7.6% of original oil in place) in that situation. Numerous injection wells have been operated in a fractured basement with a high compensation coefficient, and it helps to slow down the decline of reservoir pressure. Since 1998, the reservoir pressure has always been kept higher than bubblepoint pressure, at approximately 10 atm. As a result, the production rate remained stable (10 to 11 million tons/yr of oil). The cumulative injected water and cumulative oil production in the fractured basement up to 1 January 2010 are shown in **Fig. 14.** However, it is important to note that the relationship between the compensation coefficient and reservoir pressure may be eliminated in some regions because of the high heterogeneity of the fractured basement reservoir and poor hydraulic connections.

Discussion Concerning the Results of Waterflooding in the Fractured Basement Reservoir

The Advantage of Artificial Water Buffers in Maintaining the Average Reservoir Pressure. The basement-granite NFR has been producing since September 1988, but the reservoir pressure decreased by approximately 130 atm in 6 years. In order to maintain an effective formation pressure, waterflooding was applied in this reservoir beginning in June 1993. The effect of waterflooding strongly depends on geological characteristics and the number and distribution of injection wells. **Fig. 15** compares the average reservoir pressure in production wells of the northern structure and the central structure of the fractured basement reservoir. Because of poor hydraulic connections and lack of injection wells, the reservoir pressure quickly decreased initial production until November 1994 in the northern structure, in which one injection well operated and partly inhibited the decline of the reservoir pressure. Even though the volume of the injected water increased significantly, the reservoir pressure still went down and varied in a range from 45 to 214 atm. The low reservoir pressure in some parts of the northern structure proved that the granite basement was divided into numerous zones with poor hydraulic connection. On the other hand, the hydraulic connection in the central dome was good. It is reflected in the effectiveness of the injection pattern; the reservoir pressure is from 226 to 234 atm. In 2005, the reservoir pressure in some wells sharply increased in comparison with that in 2004 because of the increase of injected water. Up to 1 July 2007, the average reservoir pressure of the central structure was approximately 230 atm.

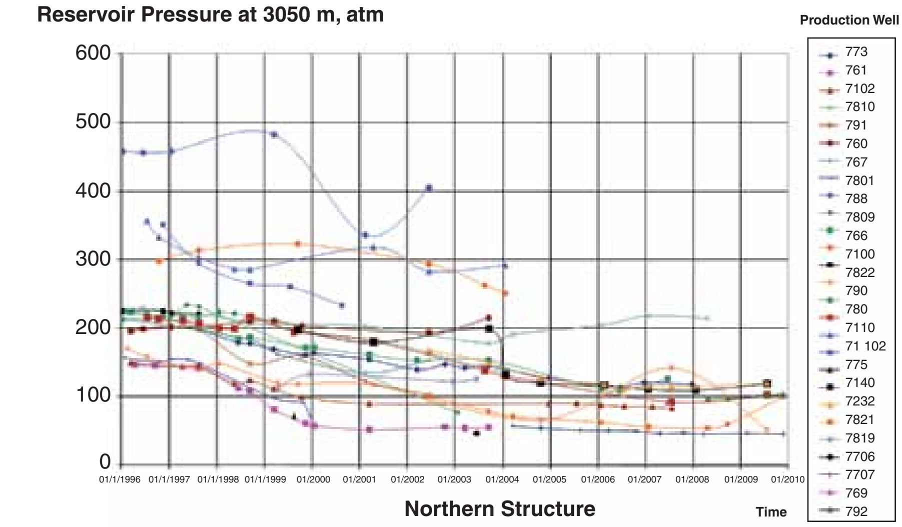
Waterflood Dynamics of Production Wells. The high heterogeneity and complex development of the fracture system causes an extreme heterogeneity of permeability and hydrocarbon reserves. This leads to flooding problems of production wells becoming more complicated. There are three groups that describe the dynamics of water cut in the basement reservoir of the White Tiger field.

(1) The group of production wells with a rapidly increasing water cut **(Fig. 16):** This group holds approximately 70% of the production wells. All water-cut curves are vertical and quickly increased after a short time. Some studies were conducted to conclude that the wells in this group had a high flow rate with a short operating length and high permeability. A promising method for producing in this area is to shut or isolate the reservoir and perforate in the upper part, if this part has an interval opening to the basement. This method was applied in numerous production wells (e.g., 7430, 7404, 7410, 7409, 7413, 7428, and 7420) with good results, as shown in **Table 4.** As a typical example, injected water has been found in Well 7420 at the end of 1998 at 3380 m in depth. Then, the well was reperforated at 3239 m in depth and has produced approximately 1.5 million tons of oil without the presence of water. The oil-production rate generally increases significantly after treatment. However, this method is highly effective only for perforated-completion wells. Water cut was again quickly increased and the incremental oil production is minimal in openhole-completion wells. Cyclic waterflooding was also tested, with positive results in some production wells (7314, 7704, 7308, 7439, and 7479).

(2) The group of production wells with an unstable water cut **(Fig. 17):** This group holds approximately 15% of total production wells. The water cut in the wells of this group increased slowly. The water cut in some wells even decreased at a different rate. The analysis showed that this group had a medium flow rate with a long operating length and permeability isolated in a broad range.

(3) The group of production wells with decreasing water cut **(Fig. 18):** There are eight wells in this group. The decreasing water cut was observed as a result of optimizing the amount of the injected water. Sometimes, stopping the waterflooding also decreased water cut in the production well. In the fractured basement reservoir, water usually moves along the fracture system, having high permeability, and the water cut strongly increases after it exceeds 10%. Thus, maintaining a low water cut level is important and may become a challenge for the operation of these oil fields.

Until now, AWOC in the basement reservoir has been located at 3566 m or has even moved to 3400 m in depth in the southwest regions. The distance between the AWOC and production zone is approximately 200 to 400 m **(Fig. 19).** The speed of water-cut rise depends on three main factors: geological characterization, perfo-



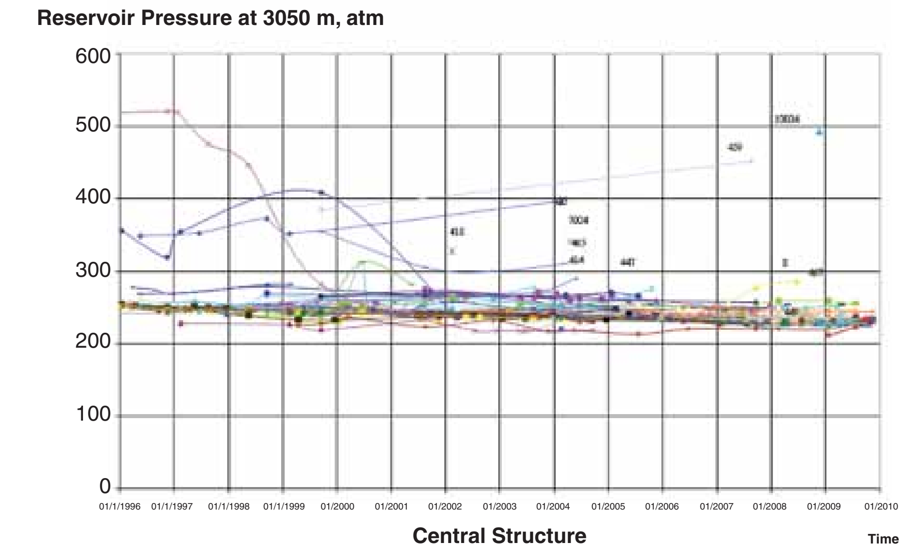


Fig. 15—Dynamic reservoir pressure in the production wells of northern and central structures.

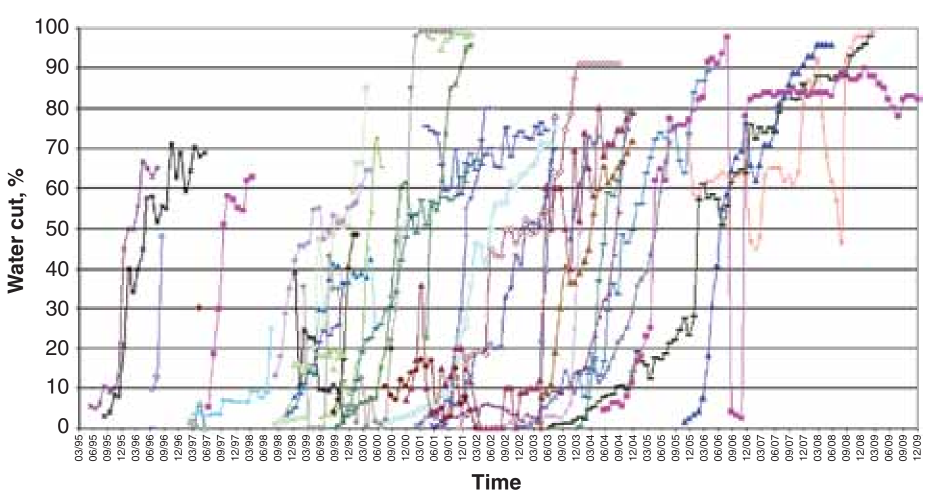


Fig. 16—Group of production wells with the quickly increasing water cut.

TABLE 4—PRODUCTION STATUS AFTER REPERFORATION IN UPPER LAYERS				
Production Well	Reperforation Day	Perforated Depth (Old/New, m)	Oil Rate Before and After Reperforation (tons/D)	Water Cut Before and After Reperforation (%)
7430	May, 1997	(3415–3515) (3271–3369)	360/600	48/0
7404	July, 1997	(3340–3745) (3108–3511)	120/560	6/0.3
7410	July, 1997	(3483–3733) (3273–3524)	5/57	30/10
7409	May, 1998	(3330–3490) (3171–3331)	31/710	65/0
7413	July, 2000	(3611–3778) (3231–3388)	250/780	25/0
7428	June, 2000	(3440–3695) (3241–3453)	250/900	64.3/0
7420	July, 2000	(3408–3506) (3239–3336)	637/850	25/0

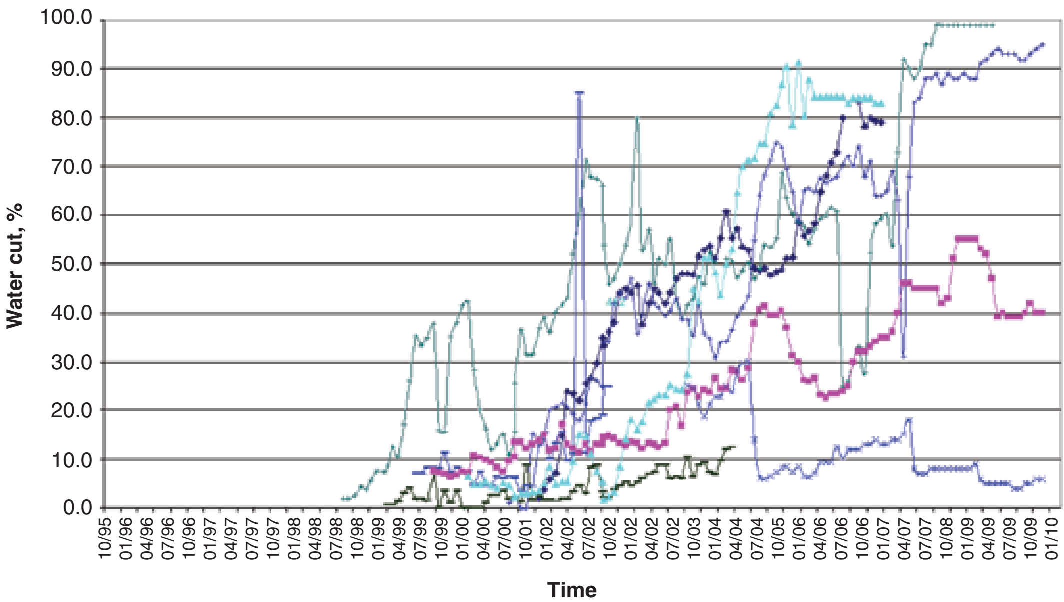


Fig. 17—Group of production wells with unstable water cut.

ration and operated length, and the relationship between the pressure gradient and gravity force. Although water was injected in the bottom of reservoir, the strike of faults and fractures mainly developed at 40 to 60º. Thus, the injected water could easily move to production wells that are located near fractured zones. In combination with high permeability in the fracture systems, it is a great danger to the lift of production wells. Therefore, controlling water cut is of urgent importance in order to extend the field life.

Conclusions

This paper introduces the important geological characterization and development of the waterflooding concept in a fractured basement reservoir. Specifically, the following conclusions are reached:

- The fractured basement reservoir of the White Tiger field is one of the most unique reservoirs in the world, having huge hydrocarbon reserves in the basement-granite reservoir. The geological characterization of this reservoir is extremely complex; thus, it is a challenge for waterflooding and EOR in this reservoir.
- On the basis of a detailed understanding of geological characterization, a successful design for waterflooding in this fractured basement reservoir has been proposed. After 7 years, a large-scale artificial water buffer was generated in the bottom of the fractured basement reservoir. This approach overcomes the difficulty of geological problems, effectively maintains the reservoir pressure, and significantly increases the oil recovery factor.
- The exploitation compensation coefficient mentioned in this paper helps reservoir engineers easily determine the optimal amount of injected water required and prevents rapid flooding in production wells.
- The fracture system is one of the most important factors that control the success of the waterflooding process. Large fractures with high permeability can easily cause early breakthrough in the production wells.
- The experience of developing the waterflooding process in the White Tiger oil field provides valuable lessons for the development of other fractured basement reservoirs in the world. **JCPT**

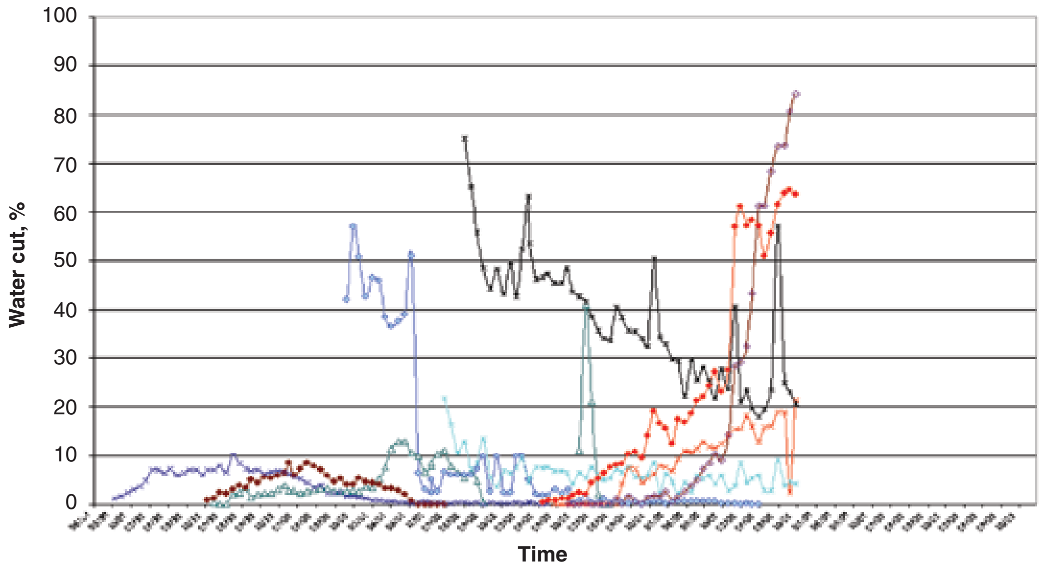


Fig. 18—Group of production wells with decreasing water cut.

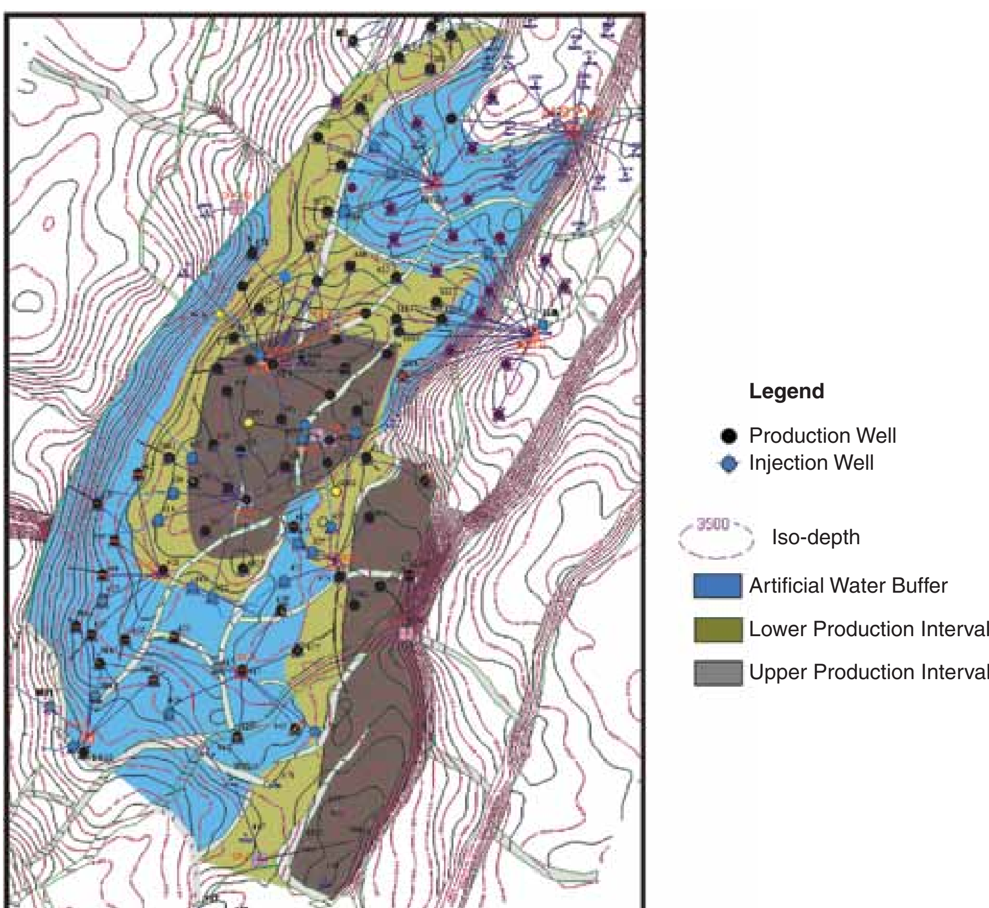


Fig. 19—Flooded water map.

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SI Metric Conversion Factor

atm × 1.013 250* E+05 = Pa

*Conversion factor is exact.

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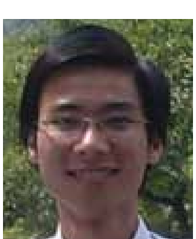

Cuong T.Q. Dang is currently a PhD degree candidate who joined the Department of Chemical and Petroleum Engineering at the University of Calgary in September 2010. He has authored or coauthored more than 40 technical and journal papers and has been serving as a technical editor for several scientific journals in petroleum engineering. Dang's research interests include EOR for conventional and unconventional reservoirs, reservoir simulation, optimization, and history matching. He holds a BSc degree in geology and petroleum engineering from Ho Chi Minh University of Technology in Vietnam and an MSc degree from Sejong University in South Korea. Dang is a member of SPE.

Zhangxing Chen is currently a professor at the University of Calgary, director of the Schlumberger iCentre for Simulation and Visualization, and holds the NSERC/AERI/Foundation CMG Senior Research Chair in Reservoir Simulation and the iCORE Industrial Chair in reservoir modelling. He formerly held a Tengfei Chaired and Chang Jiang Chaired Professorship at Xi'an Jiaotong University, a Tepin Professorship of Energy and Resources at the Peking University, Ziqiang Professorship at Shanghai University, and a Gerald J. Ford Research Professorship at Southern Methodist University. Chen's research interest is in numerical reservoir simulation, high-performance computing, mathematical modelling, and algorithm development. He holds a BS degree from the University of Jiangxi, an MS degree from Xi'an Jiaotong University in China, and a PhD degree from Purdue University, USA.

Ngoc T.B. Nguyen is currently a PhD degree candidate in petroleum engineering at Sejong University in South Korea. Since April 2003, she has been a lecturer in the Geology and Petroleum Department at Ho Chi Minh City University of Technology in Vietnam. Nguyen also worked as a reservoir geologist for Petronas Cagilary Vietnam Limited. She holds a BEng degree from Ho Chi Minh University of Technology and an MSc degree from Gadjah Mada University in Indonesia. Nguyen is a member of SPE.

Wisup Bae is currently a professor of petroleum engineering and head of the Sejong University Energy and Mineral Resources Engineering Department in South Korea. He leads a 12-person research group that is involved in research related to problems of EOR by chemical flooding and surface facilities for steam-assisted gravity-drainage projects. Before joining the university, Bae was deputy director of the Ministry of Energy, Petroleum Division. He holds a diploma in petroleum engineering from Seoul National University and MSc and PhD degrees in petroleum engineering from The University of Texas at Austin. Bae is a member of the board of Geosystems Engineering Journal and a member of SPE.

Thuoc H. Phung is an expert at the Research and Engineering Institute, Vietsovpetro Joint Venture, in Vietnam. He has more than 20 years of experience in design and development of a gain oil field. Phung's research interests focus on reservoir simulation, history matching, and optimization of waterflooding for conventional and fractured basement reservoirs. He holds a Bachelors degree from the University of Mining and Geology in Vietnam.